

ULTRALUMINOUS INFRARED GALAXIES

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ABSTRACT. The IRAS survey of the local universe ($z \lesssim 0.1$) has revealed the existence of a class of ultraluminous infrared galaxies with $L(8-1000\mu\text{m}) > 10^{12} L_{\odot}$ that are slightly more numerous, and as luminous as optically selected quasars at similar redshift. Optical CCD images of these infrared galaxies show that nearly all are advanced mergers. Millimeter-wave CO ($1 \rightarrow 0$) observations indicate that these interacting systems are extremely rich in molecular gas with total H_2 masses $1 - 3 \times 10^{10} M_{\odot}$. Nearly all of the ultraluminous infrared galaxies show some evidence in their optical spectra for nonthermal nuclear activity. It is proposed that their infrared luminosity is powered by an embedded active nucleus and a nuclear starburst both of which are fueled by the tremendous reservoir of molecular gas. Once these merger nuclei shed their obscuring dust, allowing the AGN to visually dominate the decaying starburst, they become the optically selected quasars.

1. INTRODUCTION

Recent determinations of the luminosity function for IRAS galaxies (Lawrence *et al.* 1986, Rieke and Lebofsky 1986; Soifer *et al.* 1986) all show a significant population of luminous infrared galaxies with infrared luminosities exceeding $10^{12} L_{\odot}$ ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$). Soifer *et al.* (1986) find that at luminosities above $10^{10} L_{\odot}$ the space density of infrared galaxies is comparable to, or greater than that for active and starburst galaxies, and at the highest luminosities the IRAS galaxies are slightly more numerous than optically selected quasars (Schmidt and Green 1983). The ultraluminous infrared objects with $L(8-1000\mu\text{m}) > 10^{12} L_{\odot}$ are the subject of this paper.

The data reported here are part of a larger study of the properties of the brightest galaxies in the IRAS survey. The bright galaxy sample includes all objects brighter than 5.4 Jy at $60\mu\text{m}$ with $|b| > 30^\circ$ and $\delta > -30^\circ$. Because these are the brightest galaxies in the sky at $60\mu\text{m}$, this sample represents the best opportunity for the study of the infrared emission processes in galaxies. A complete description of the survey and the luminosity function for these galaxies is given in Soifer *et al.* (1986, 1987). A preliminary description of the morphology and molecular gas content of 'high luminosity' members of the bright galaxy sample with $L_{\text{FIR}}(40-400\mu\text{m}) = 6 \times 10^{10} - 6 \times 10^{11} L_{\odot}$ is given in Sanders *et al.* (1986a).

2. THE ULTRALUMINOUS IRAS GALAXY SAMPLE

The ultraluminous objects in the IRAS Bright Galaxy Survey are listed in Table 1. Their tabulated luminosity was computed using the prescription outlined by Perault *et al.* (1986) which uses the data from all four IRAS bands to approximate $L(8-1000\mu\text{m})$. Since several of the ultraluminous objects have substantial flux at $25\mu\text{m}$, this method provides a significantly better approximation to the bolometric luminosity than the more commonly used L_{FIR} fit to the 60 and $100\mu\text{m}$ data given in *Catalog of Galaxies*

and Quasars Detected in the IRAS Survey (1985). The dominance of the far infrared luminosity in the total energy budget for all of the ultraluminous galaxies can be seen from the tabulated ratio $\nu f_{\nu}(80)/\nu f_{\nu}(B)$ which has a median value of 25.

Table 1
Ultraluminous IRAS Galaxies

Object	RA (1950)	Dec (1950)	cZ ^a (km s ⁻¹)	L(8-1000 μ m) (10 ¹²)L _⊙	$\frac{\nu f_{\nu}(80)}{\nu f_{\nu}(B)}$	Morph ^b	Optical ^c Spectra
IRAS	05 18 58.6	-25 24 40	12706	1.23	24	star	Sey 1.5
IRAS	08 57 13.0	+39 15 40	17480	1.25	10	M	HII
UGC5101	09 32 04.6	+61 34 37	12000	1.02	22	M	Sey 2
IRAS	12 11 12.2	+03 05 20	21703	1.94	68	M	LINER
Mrk231	12 54 04.8	+57 08 38	12623	3.45	22	M	Sey 1
Mrk273	13 42 51.6	+56 08 13	11400	1.47	33	T	Sey 2
IRAS	14 34 52.3	-14 47 24	24332	1.88	33	M	LINER/HII
IRAS	15 25 03.1	+36 09 00	16009	1.00	25	M	LINER
Arp220	15 32 46.3	+23 40 08	5450	1.58	59	M	Sey 2
IRAS	22 49 09.6	-18 08 20	22807	1.33	25	M	LINER

Note: Objects in the IRAS Bright Galaxy Survey (Soifer *et al.* 1986, 1987) with $L(8-1000\mu\text{m}) \geq 10^{12}L_{\odot}$

^aMean optical heliocentric redshift

^bM - advanced merger; tidal tails observed.

T - single long tail of Mrk 273 due to recent strong interaction with disturbed companion 2' North.

star - appears star-like on Palomar print; obvious nebulosity on short CCD exposure.

^cBased on linewidth of H α + [NII] and/or [OIII]/H β line ratio from long-slit spectrum.

The majority of the objects in Table 1 have blue magnitudes greater than 15.5, hence are not found in the standard catalogs. The mean redshift of the sample is $\sim 16,000 \text{ km s}^{-1}$. The space density of these objects in the local universe ($z < 0.081$) is $\rho \sim 10^{-7} \text{ Mpc}^{-3} M_{\text{bol}}^{-1}$. The sample of objects listed in Table 1, although relatively small, is an impressive number when one realizes that the only other objects in the same volume of space of comparable luminosity are quasars of which there are only about half as many.

3. BASIC PROPERTIES OF ULTRALUMINOUS IRAS GALAXIES

We have undertaken a major program of optical, near-infrared and radio continuum observations of all of the galaxies in the bright galaxy sample in an attempt to understand both the nature of the host galaxy and the origin of the enhanced infrared radiation in the most luminous objects. Data for the ultraluminous sample are summarized here with a more complete accounting to appear in Sanders *et al.* (1987).

3.1 IMAGING

One of the most important results of the entire IRAS Bright Galaxy Survey is that nearly all of the ultraluminous objects appear to be merging spirals. Eight of the ten objects show obvious, long tidal tails which extend from almost completely merged disks. The symmetry and length of the tails are reminiscent of numerical simulations of mergers between two disks of nearly equal mass (e.g. Toomre and Toomre 1972). One of the remaining two objects, Mrk 273, has a single, long tail pointing directly away from an extremely blue, nearly point-like companion. The companion has apparently scored a direct hit on Mrk 273, leaving behind most of its disk gas to what is now seen as a heavily reddened, disturbed galaxy. The remaining ultraluminous object, IRAS 0518-25, appears stellar on the Palomar Sky Survey print, but shows distinct nebulosity on a short CCD exposure. A deeper image is required to detect evidence of a merged system.

Figure 1 shows deep CCD images of Arp 220 and Mrk 231 - the two galaxies from our list that have attracted considerable past interest because of their extreme infrared properties. Previous optical images have apparently not been deep enough to show the faint tidal tails that clearly implicate a recent merger as the trigger for the extreme luminosity of these objects.

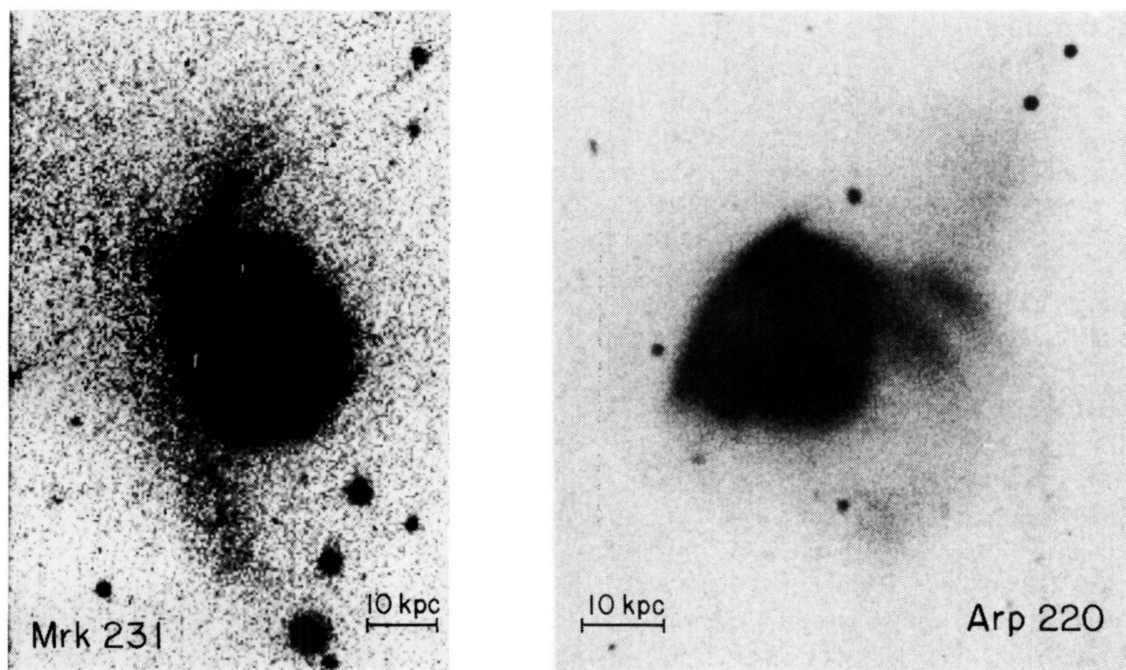


Figure 1: CCD images at 6500\AA (Gunn *r*) of Arp 220 and Mrk 231. The scale is approximately $0''.5/\text{pixel}$ and seeing was ~ 1 arcsec.

3.2 OPTICAL SPECTRA

High-resolution, long-slit optical spectra (3800-8000Å) have been taken of the ultraluminous galaxies using the CCD double spectrograph on the Palomar 5m telescope. All are strong emission-line objects. Broad H α emission was the primary diagnostic used to identify Seyfert activity. The remaining galaxies with narrow emission lines most often show [OIII]/H β line ratios characteristic of a LINER spectrum. Only one object bears strict resemblance to a thermal HII region spectrum. One galaxy has two clearly separable nuclei, one with a liner spectrum and the other of HII region type.

Our classification of the optical spectra is rather simplistic as several of these ultraluminous objects appear to have a mixture of nonthermal and thermal emission components. The most bizarre spectrum is that of Mrk 231 which shows broad H α emission plus several strong absorption bands indicating a possible circumnuclear starburst (c.f. Boksenberg *et al.* 1976). Several other objects, most notably Arp 220 (Rieke *et al.* 1984), appear to have both strong thermal and nonthermal components, but in Table 1 we have emphasized nonthermal emission. As a class, the ultraluminous infrared galaxies differ dramatically from the majority of the galaxies with lower luminosity discovered by IRAS. The vast majority of the bright galaxies surveyed by us (Sanders *et al.* 1987) as well as the IRAS mini-survey galaxies studied by others (Elston, Cornell, and Lebofsky 1985; Lawrence *et al.* 1986) are narrow emission line objects with HII region type optical spectra.

3.3 ENERGY DISTRIBUTION

We have combined the IRAS data with ground-based optical and near-infrared photometry to determine the energy spectrum between 0.44 and 100 μ m for all of the ultraluminous galaxies as shown in Figure 2. The dominance of the far-infrared emission ($\lambda > 40\mu$ m) in the total energy budget ranges from >95% for Arp 220 to ~50% in Mrk 231.

The distributions in Figure 2 are displayed approximately in order of increasing $f_\nu(60\mu\text{m})/f_\nu(100\mu\text{m})$ ratio of flux densities. The 60 μ m and 100 μ m IRAS data points have been fit with a single temperature dust emission ($\epsilon \propto \lambda^{-1}$) curve; dust temperatures range from 47 K for Arp 220 to 62 K in IRAS 0857+39. There is an obvious trend of increasing 12 μ m and 25 μ m emission with increasing $f_\nu(60\mu\text{m})/f_\nu(100\mu\text{m})$ color temperature, possibly due to a separate component of hotter dust associated with a Seyfert nucleus (c.f. Miley, Neugebauer, and Soifer 1985). There is also an obvious trend of increasing 1-5 μ m flux with increasing far-infrared color. This may still represent thermal emission from high temperature dust relatively close to a luminous nonthermal nuclear source, or it could be nonthermal emission directly associated with the region emitting the broad optical emission lines.

3.4 MOLECULAR GAS

Because of the relatively large distance of most of the ultraluminous objects and the limited sensitivity of current single dish millimeter-wave telescopes, direct measurement of the molecular gas content is limited to two objects – Arp 220 and Mrk 231. However, these data are extremely interesting in that both Arp 220 and Mrk 231 are among the most luminous CO sources known and their ratio of infrared luminosity to total H $_2$ mass is more extreme than observed in other high luminosity IRAS galaxies. Figure 3 shows that the total mass of H $_2$ in Mrk 231 is $1.4 \times 10^{10} M_\odot$ and the $L_{\text{FIR}}/M(\text{H}_2)$ ratio of 150 is ~35 times larger than that found for the ensemble of molecular clouds in the Milky Way (Sanders *et al.* 1986a; Scoville and Good 1986). For Arp 220 the values are $M(\text{H}_2) = 1.43 \times 10^{10} M_\odot$ and $L_{\text{FIR}}/M(\text{H}_2) = 95$ (Young *et al.* 1984; Sanders and Mirabel 1985. If the $L_{\text{FIR}}/M(\text{H}_2)$ ratio measures the efficiency of star formation (Sanders and Mirabel 1985; Young *et al.* 1986) then their molecular gas will be depleted in $\sim 10^8$ years.

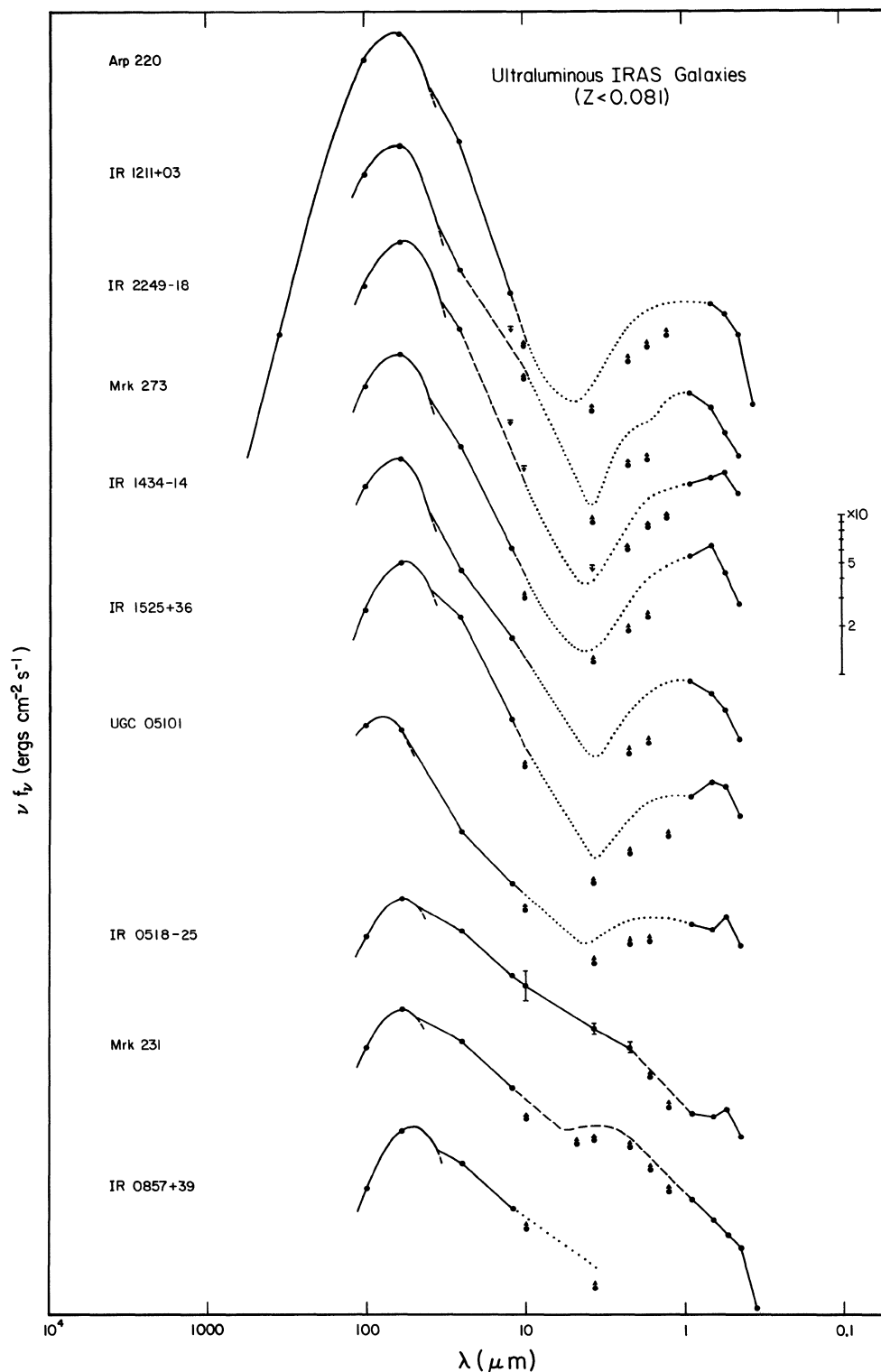


Figure 2: Spectral energy distributions from 0.33 to 100 μm for ultraluminous infrared galaxies in the IRAS Bright Galaxy Survey. The data from 0.44 to 100 μm is from this work. Additional data for Arp 220 at 350 μm and 760 μm are from Emerson *et al.* (1984). The 1-10 μm data points are 5'' or 10'' aperture measurements. The shape of the energy distribution of the entire galaxy between 1 and 10 μm (dotted line) was estimated from these small aperture measurements and the measured magnitude growth curve at I (0.88 μm).

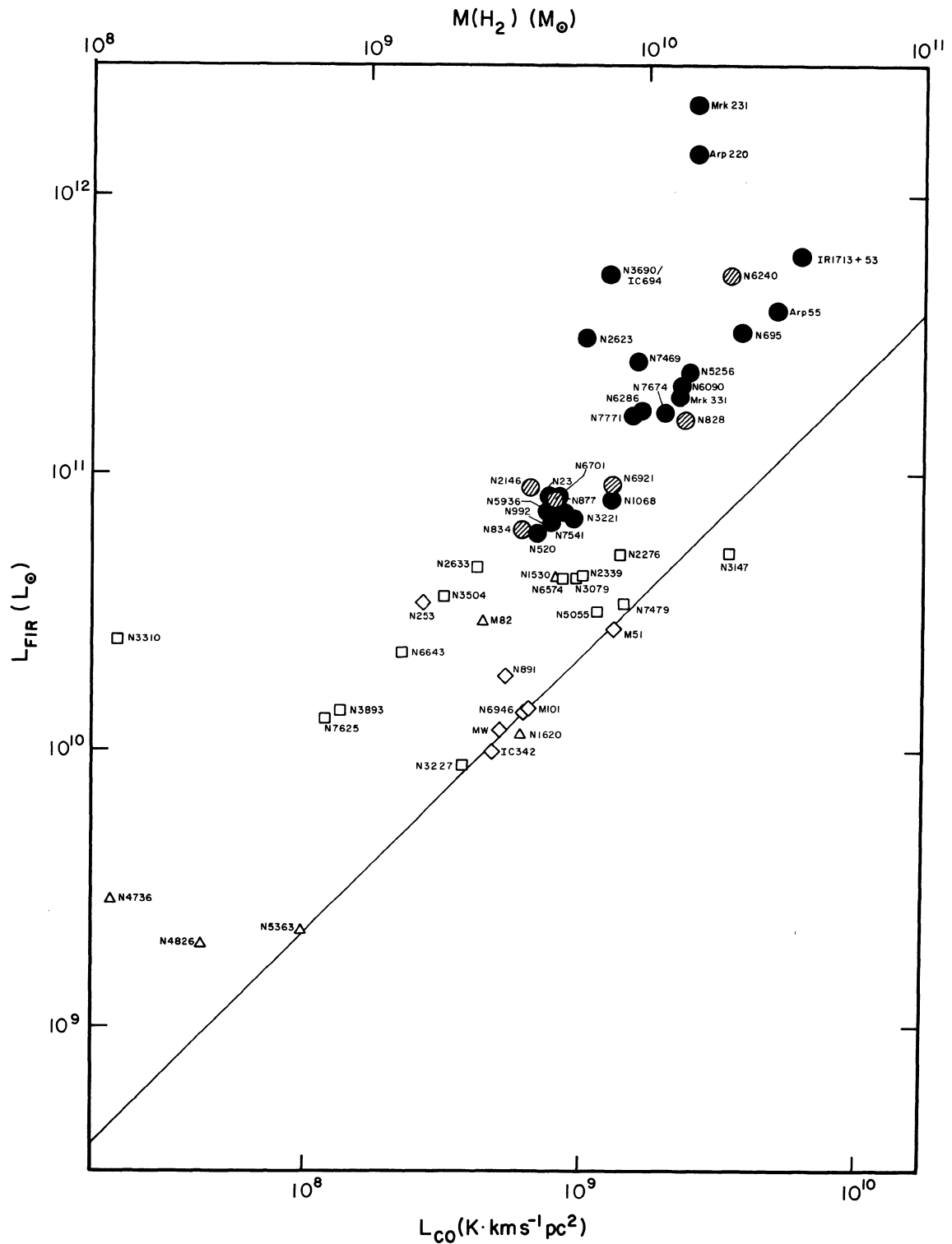


Figure 3: The total far-infrared luminosity determined from IRAS data vs CO luminosity and the total mass of H_2 in molecular clouds. Circles represent high luminosity IRAS galaxies which are an unbiased sample of all galaxies with $L_{FIR} (40-400\mu m) \geq 7 \times 10^{10} L_{\odot}$. All other symbols represent CO observations of lower luminosity bright IRAS galaxies with known and unknown selection bias (see Sanders *et al.* 1986a).

4. DISCUSSION

The ultraluminous infrared galaxies represent the culmination of a trend toward an increasing percentage of interacting spirals with increasing infrared luminosity that has already been observed in previous studies of IRAS galaxies at lower luminosity (Sanders *et al.* 1986a). Table 2 compares the properties of the ultraluminous sample with galaxies at lower luminosity from the IRAS Bright Galaxy Survey. In addition to the increased frequency of merger candidates, there is evidence from the optical spectra that non-thermal AGN's play an increasing role in the energy budget at the highest luminosities.

Figure 3 strongly suggests that the fuel for the infrared luminosity in all of the bright IRAS galaxies is an abundant supply of molecular gas. Several possibilities exist for producing this luminosity, particularly if both collision partners were initially rich in molecular clouds. During the merger molecular clouds in the disks of the two spirals would be expected to undergo frequent collisions, potentially generating infrared luminosity directly (Harwit *et al.* 1986) and/or triggering massive star formation (Scoville, Sanders, and Clemens 1986). In addition, if the collision trajectory has the two galactic disks counter-rotating then the cancellation of angular momentum during cloud-cloud collisions should result in a pile-up of molecular material near the merger nucleus. This may further enhance the 'starburst' and supply fuel for a QSO nucleus. Recent CO observations of Arp 220 with the OVRO millimeter-wave interferometer (Scoville *et al.* 1986), show that most ($> 70\%$) of the CO emission comes from a radius smaller than 750 pc centered on the bright radio and near-infrared nucleus.

Table 2
IRAS Galaxy Properties vs Increasing Infrared Luminosity^a

Property		$(2 - 7 \times 10^{10} L_{\odot})$	HL $(7 \times 10^{10} - 7 \times 10^{11} L_{\odot})$	UL $(> 10^{12} L_{\odot})$
No. Objects (BG Sample)		80	80	10
Morphology	merger	10%	40%	90%
	close pair	15	30	10
	isolated	75	30	0
Optical Spectra	Seyfert	$< 10\%$	20%	50%
	LINER/?	} > 90	} 80	40
	HII			10
$\nu f_{\nu}(80)/\nu f_{\nu}(B)$ (median)		1	5	25
$L_{FIR}/M(H_2)$ (median)		5	18	120

^aInfrared luminosity = $L(8-1000\mu m)$. Data for $2 - 7 \times 10^{10} L_{\odot}$ galaxies and High Luminosity sample is from Sanders *et al.* (1986a, 1987).

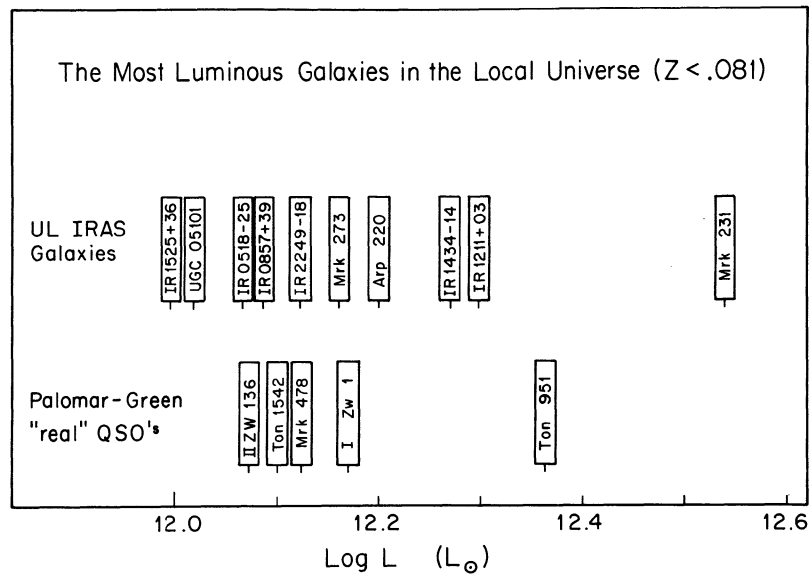


Figure 4: Objects with luminosities greater than $10^{12} L_{\odot}$ at $z \leq 0.081$. For the infrared galaxies the plotted value is $L(8-1000\mu\text{m})$ which is $\approx 0.9 L_{\text{Bol}}$. For the optically selected quasars (Schmidt and Green 1983) the luminosity is L_{Bol} as determined by Soifer *et al.* (1986).

As the most luminous infrared objects in the local universe the ultraluminous IRAS galaxies are all at, or near their peak luminosity. It appears likely that this coincides with a dense and massive concentration of molecular gas around a merger nucleus which is heated by both an embedded AGN and newly formed massive stars. Eventually this gas will be dispersed through the combined action of supernova explosions, stellar winds, and radiation pressure. Such housecleaning may have already begun in those objects listed in Table 1 whose broad-line Seyfert spectra suggest that we can see into the central nonthermal source. It seems reasonable to assume that these galaxies will shortly resemble optically selected QSO's characterized by a dominant central point source. The infrared-loud quasar IRAS 1334+24 (Beichman *et al.* 1986) might well represent just such a state. Figure 4 compares the total number of ultraluminous infrared objects and their luminosities with the bolometric luminosities of a complete optical sample of QSO's within approximately the same volume of space. If the lifetimes of the ultraluminous infrared and QSO phases are approximately equal, then Figure 4 suggests that nearly all ultraluminous infrared galaxies become QSO's and that the QSO phase may in fact be slightly less luminous than the infrared phase.

5. ACKNOWLEDGEMENTS

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DISCUSSION

Thronson: How does the following selection effect affect your interpretation of your plot of L_{IR} vs L_{CO} , if at all: in a flux-limited sample, would you not tend to be strongly biased toward high-efficiency of star formation?

Sanders: Our flux limited sample is biased toward selecting objects with high L_{FIR} , whatever the cause of the FIR. Figure 2 should not be used to determine the true distribution of $L_{\text{FIR}}/L_{\text{CO}}$ at a given L_{CO} , particularly at $L_{\text{FIR}} \leq 7 \times 10^{10} L_{\odot}$ where we have simply plotted all galaxies for which CO data was available from the literature plus a few of our own. However, above $L_{\text{FIR}} \sim 10^{11} L_{\odot}$ where most of the plotted data is from our Bright Galaxy survey, we attempted to uncover additional galaxies of comparable far-infrared luminosity which lie within the boundaries of the survey, by lowering the $60 \mu\text{m}$ limit to 0.5 Jy . But, essentially no new objects were found. Therefore, the Bright Galaxy sample does appear to give an accurate picture of the real distribution of $L_{\text{FIR}}/L_{\text{CO}}$ at these high far-infrared luminosities.

Mundy: We have observed the nuclear region of NGC 253 in CO with the Owens Valley Interferometer. The CO emission is in a $40'' \times 10''$ bar with $L_{\text{IR}}/M_{\text{gas}} \sim 60$. Where does this fit in your sample and can't bars be very efficient at stirring up star formation?

Sanders: The data point for NGC 253 in Figure 2 represents the average $L_{\text{FIR}}/L_{\text{CO}}$ over the inner 6 arcmin radius. Apparently, the small bar in your data has a ratio yet 3 times higher, which could presumably be due to either an increase in star formation efficiency, or heating from a non-thermal nucleus.

Mezger: You showed a diagram of M_{H_2} vs L_{IR} , which deviates from a linear relation at the high luminosity end. This is in disagreement with a similar diagram shown by Krugel *et al.* (this symposium). The major difference is that you determined M_{H_2} from the (optically thick) ^{12}CO line while Krugel *et al.* uses the (optically thin) $\lambda 1300 \mu\text{m}$ dust emission. My question is: What makes you believe that you can extrapolate a relation between CO luminosity and H_2 column density, originally derived for our Galaxy, to galaxies which appear to have a gas content of two to three orders that of our Galaxy?

Sanders: I believe that the total I_{CO} from a galaxy is essentially influenced by the number of clouds. If the *mean* internal cloud properties (temperature, density, etc.) were to vary greatly from galaxy-to-galaxy then $M(\text{H}_2)$ as derived using the mean value of $M(\text{H}_2)/L_{\text{CO}} = 5.8$ found for the Milky Way would not be very accurate. For one of the most luminous galaxies in Figure 2, Arp 220, we have been somewhat surprised that our mass estimate agrees so closely with the mass determined by Emerson from $350 \mu\text{m}$ observations. The criticism raised most often concerning extragalactic H_2 masses is that ^{12}CO may be partially optically thin, a possibility that, presumably, is raised by the relatively large $^{12}\text{CO}/^{13}\text{CO}$ ratio observed in M82. Krugel's work to which you refer is the first I have seen which gives substantially larger H_2 masses than we derive from ^{12}CO .